Tool Wear Stabilization to Reduce Mid-Spatial Frequency Errors in Aspheric Grinding

NASA Mirror Tech Days
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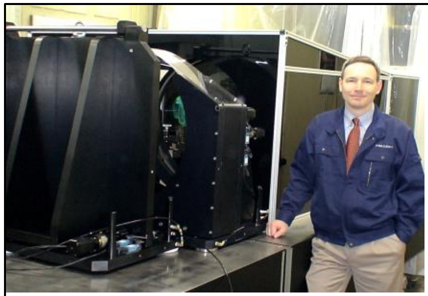
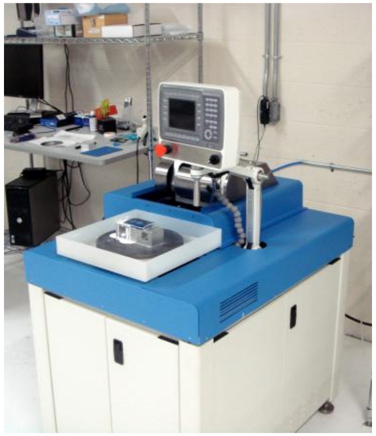
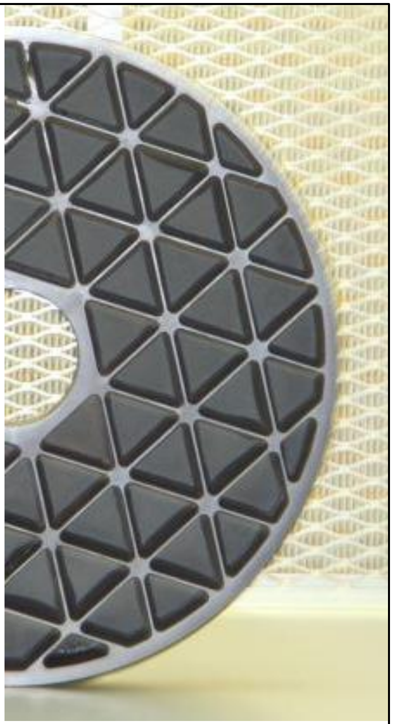
AOS Business Areas



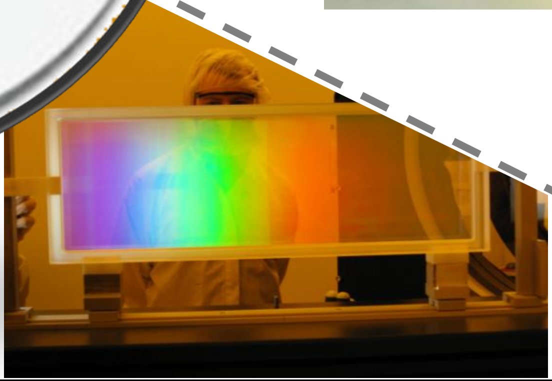
- Custom Optical Equip. & Software
- Metrology Test Fixtures & Mounts



- Silicon Carbide Optics
- Aspheric Optics
- Fast-turn prototyping



- Laser Optics
- Grating Substrates
- Stage Mirrors & Lightweight Mirrors
- Reference Flats and Spheres



NASA SBIR/STTR Technologies

Proposal No. S2.05-8494 – ELID Grinding of Large Aspheres

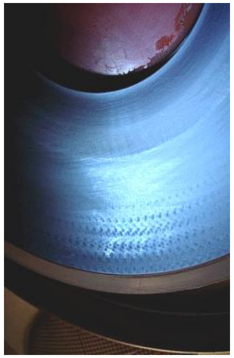
PI: Kai Xin PhD

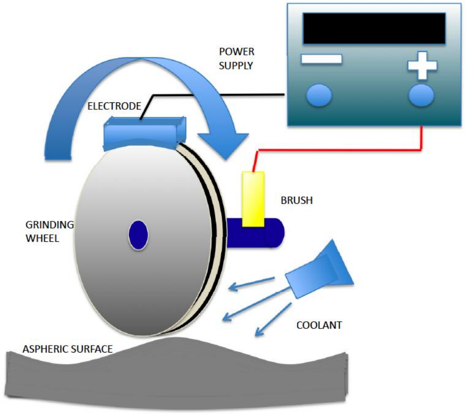
Flemming Tinker Inc. / Aperture Optical Sciences Inc. – Durham, CT

Identification and Significance of Innovation

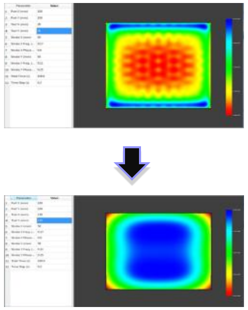
Mid-spatial frequency (MSF) and High spatial frequency (HSF) surfaces errors in the grinding of fast aspheres are amplified in hard ceramics like SiC due to cyclic tool wear rates, vibration, and tool deformation. Flemming Tinker LLC – Aperture Optical Sciences Inc. will examine Electro-Lytic In-Process Dressing (ELID) as a solution to mitigate these phenomena and reduce the creation of MSF and HSF errors. Doing so will reduce the overall cost of making fast aspheres from hard ceramics by increasing removal efficiency while subsequently reducing the need for downstream MSF error correction through smoothing.

Expected TRL Range at the end of Contract (1-9): 3-4





Technical Objectives



1. Construct ELID grinding module on conventional surface grinder
2. Model the impact of cyclic wear conditions to predict results
3. Demonstrate reduction in MSF/HSF surface errors with ELID Grinding on glass and SiC test samples
4. Determine plan for implementing on conventional large-format grinding machines for fabricating 1-3 meter size aspheric mirrors

Work Plan

1. Analytical model development
2. Preparation of experimental ELID grinder
3. Experiments on glass & SiC samples
4. Analyze results and determine plan for full-scale demonstration

NASA and Non-NASA Applications

IXO Replication Mandrels
GenX mandrels and optics
Precision Cylindrical Optics
Large Format Aspheres
Low Mid-Spatial Period Optical Surfaces
Deterministic Low Cost Fabrication

Firm Contacts

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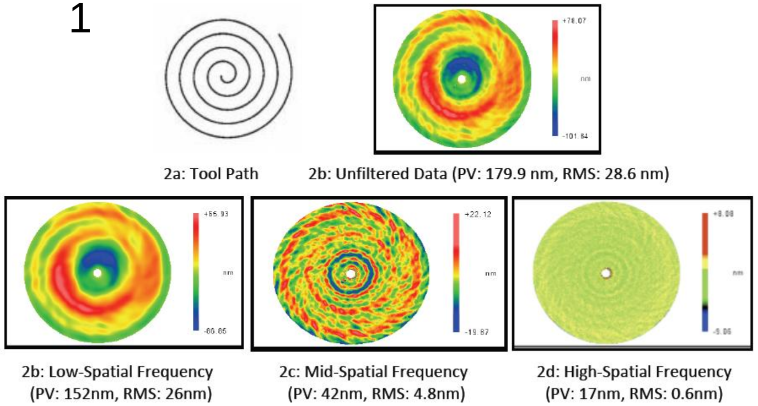
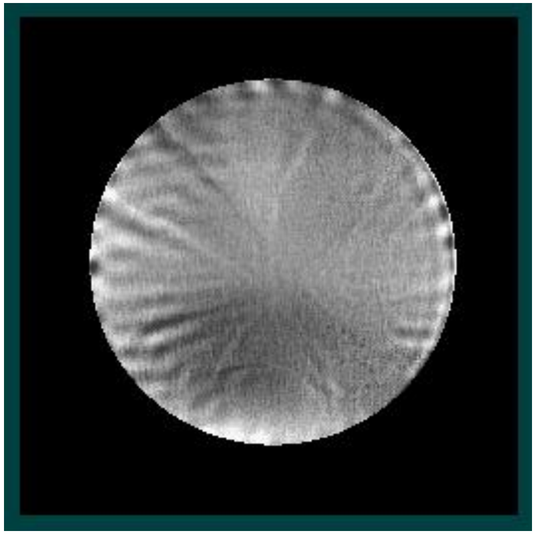
NON-PROPRIETARY DATA

- MSF and HSF surface artifacts can be created in all stages of finishing optical surfaces – particularly those employing deliberate work functions and motions.

1



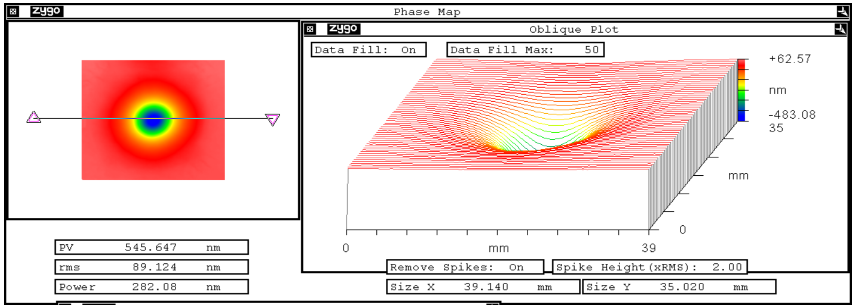
- Once created, they must be removed for optimal imaging performance through:
  - (1) Smoothing and/or
  - (2) Amplitude reduction.

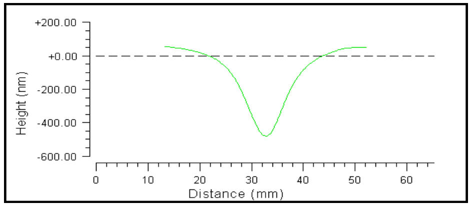


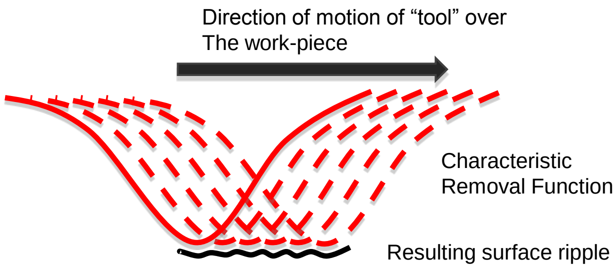
1: Youngworth, DeGroote, Aikens: OFT Sept 2008

How are MSF errors created?

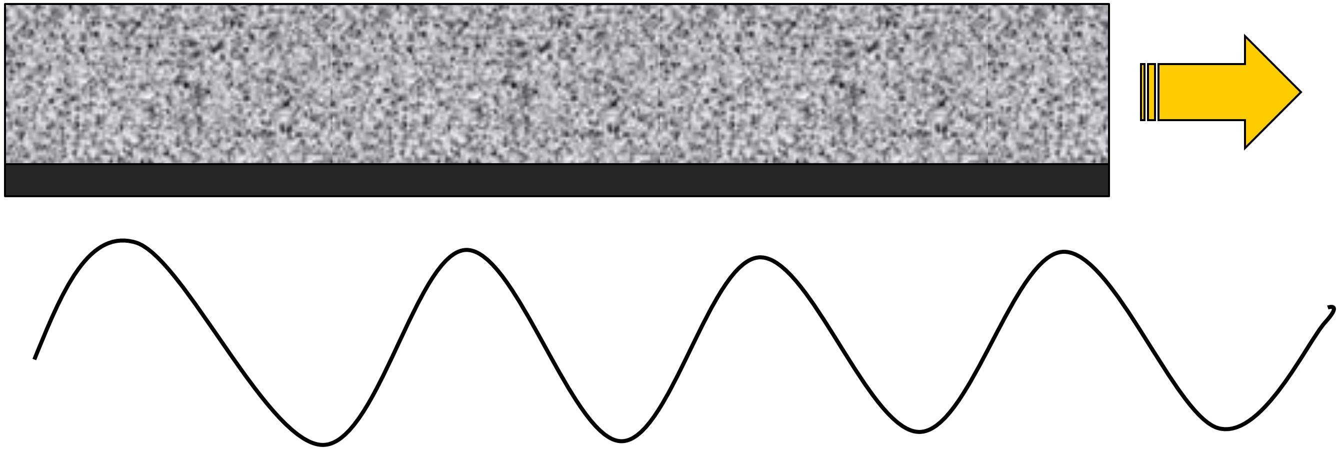
- - Overlap in rastered or spiraled sub-aperture tool paths over large surfaces
- - Machine (tool) motion control overshoot (accelerations / decelerations)
- - Machine vibration / tool resonance
- - Cyclical Tool-wear (instability)
- - Periodic patterning in work tool surface geometry
- - Tool deformation
- - Work-piece deformation
- - Print through in lightweight optics (facesheet)….
- ……….





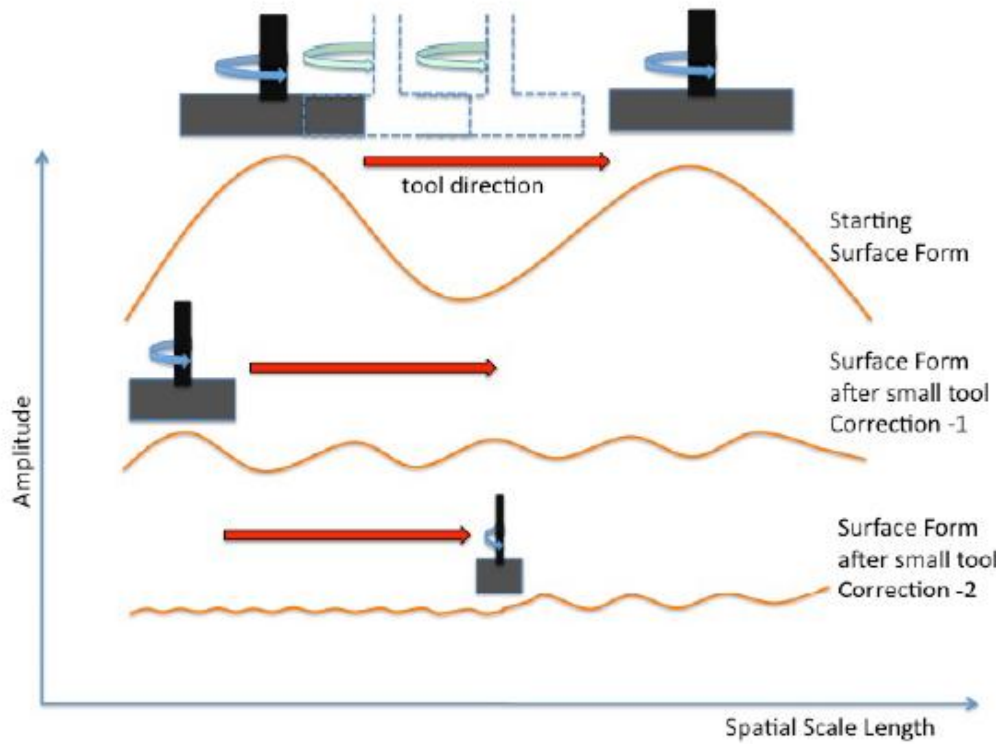


- Smoothing generally uses large tools and motions relative to the spatial scale lengths of interest - sometimes compliant materials that follow the contour of the optic



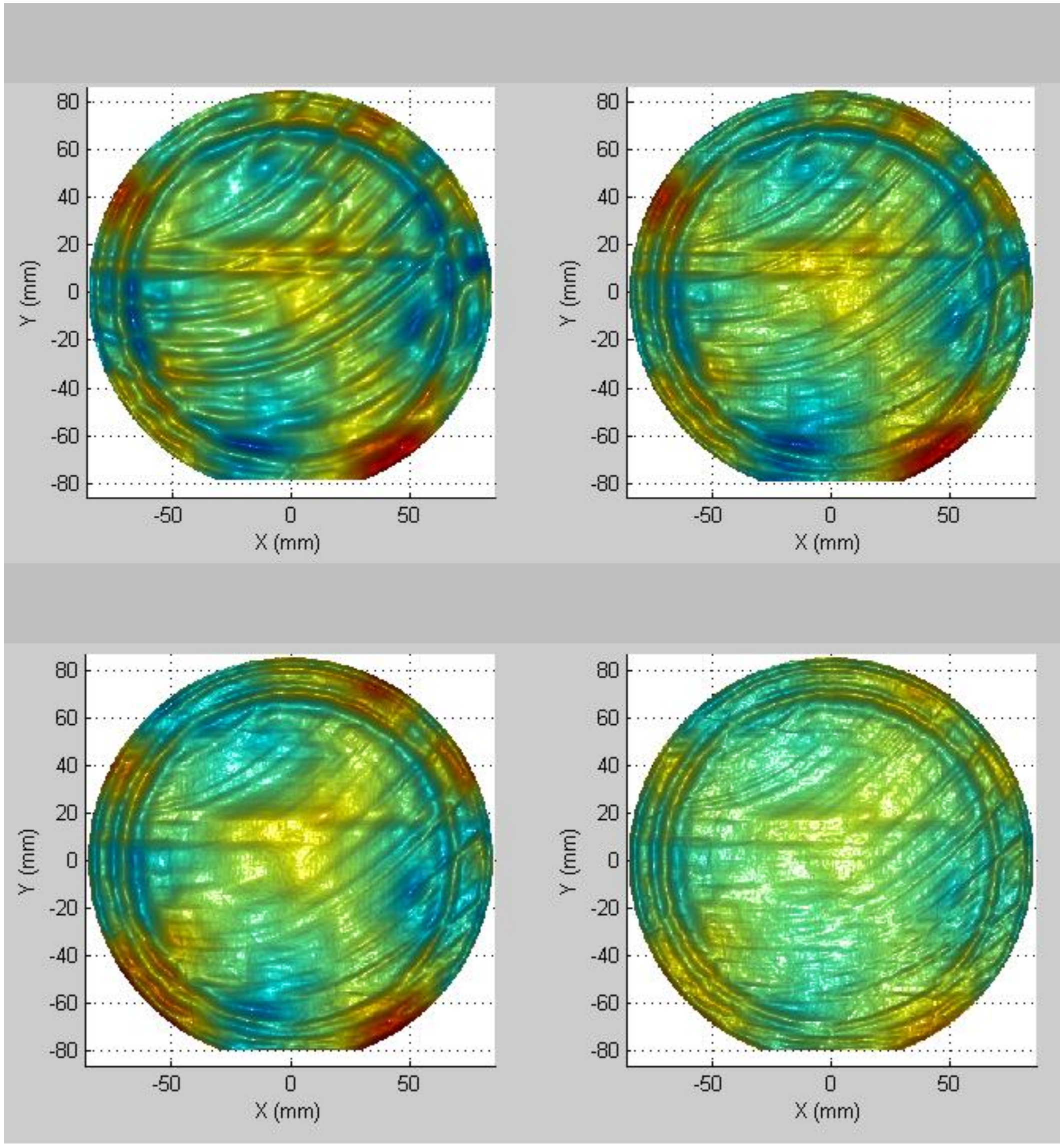
Amplitude reduction with small tools

Using smaller and smaller tools, we can reduce the amplitude of these artifacts – often with the consequence of increasing the frequency of the features in exchange for amplitude.



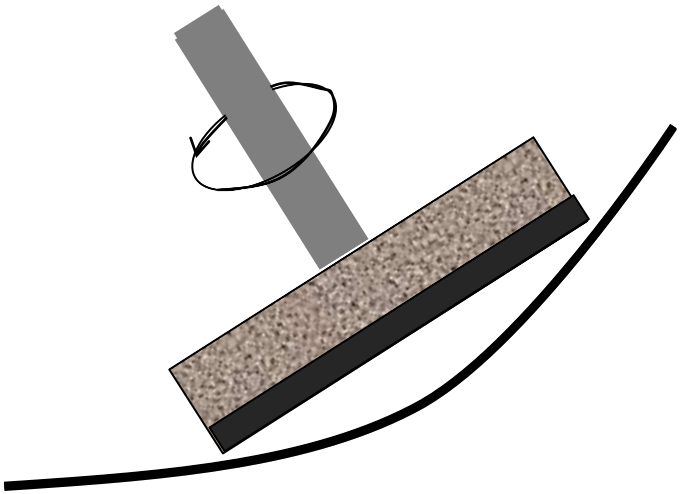
Amplitude reduction with small tools

This technique can be very effective – but it does not remove the periodicity and can actually create new and more dominant periods – its also a costly process to control.



MSF Errors are easily smoothed in flats and spheres – not so easy for fast aspheres

- Traditional optical lapping and polishing is very effective in smoothing MSF in flats and spheres due to the “randomized” tool paths and utilization of large tools.
- However, as local slopes increase such as in fast aspheres, tools must be smaller in order to follow the surface profile.



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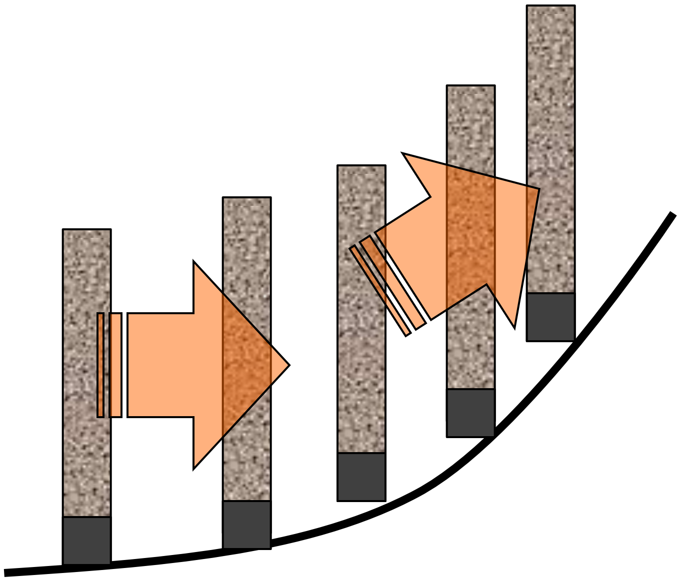

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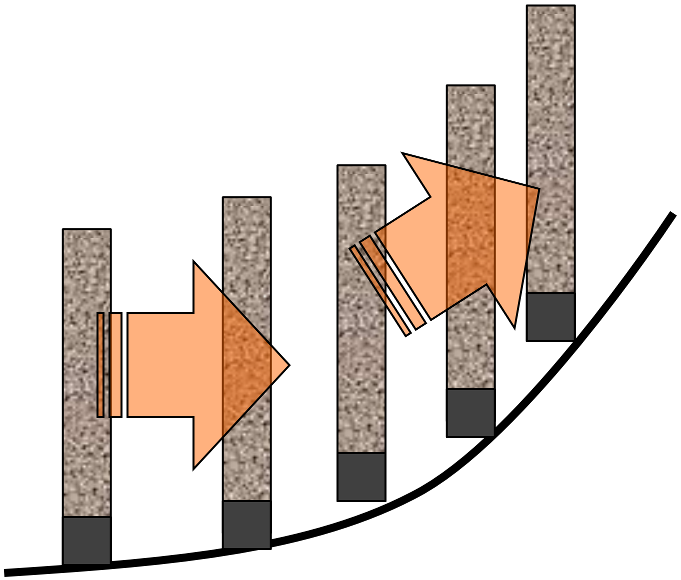
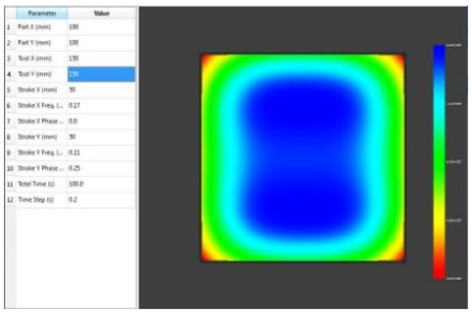


(not just important in polishing – grinding too!)

Work Function Calculator based on tool size and path

- To illustrate this point we're creating a tool path calculator as part of a custom solver that demonstrates the impact of tool size and motion on the power spectrum of surfaces.



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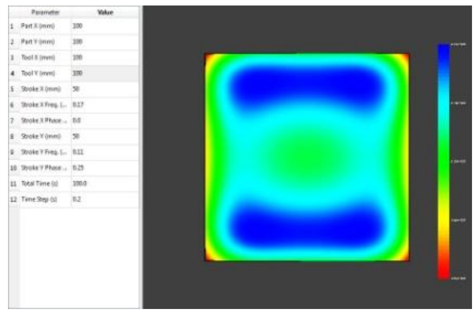

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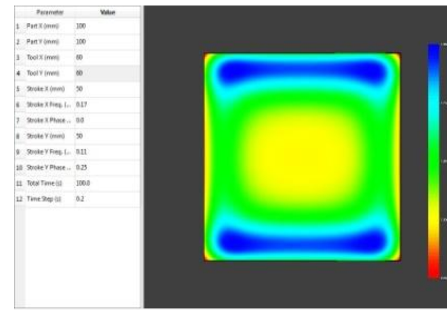
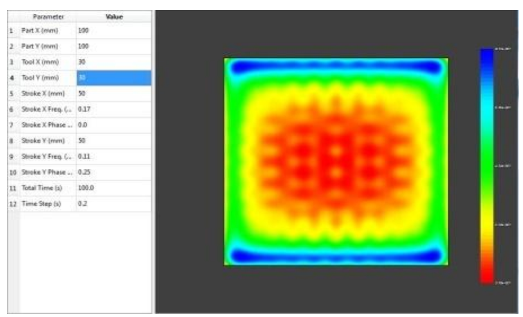


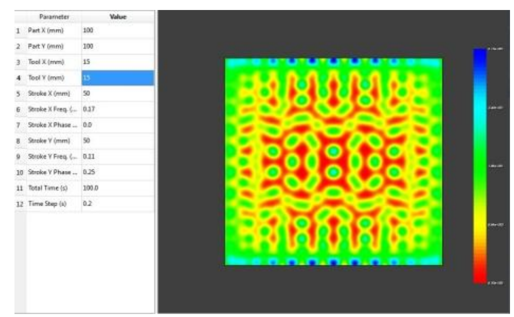
60%

Each photo shows the impact on tool to workpiece ratio:

$$\frac{\text{Area of Tool}}{\text{Area of Workpiece}}$$



30%



15%

So…

- Small tooling fabrication is necessary for grinding and polishing fast aspheres (and often for very large optics)
- Mitigation techniques are somewhat effective but often costly to implement
  - Large tool figuring is not always possible
  - Small tool correction can mitigate but is also a primary cause of new MSF/HSF errors

….But the news gets worse as we consider hard ceramics like SiC.

Mitigation of Periodic Surface Errors can be expensive

Cause of MSF Errors	Mitigation / Correction	
Overlap in raster or spiral sub-aperture tool paths	Post-grind polishing – can be very slow and limited	
Machine (tool) motion control limitations – inability to adequately follow position and acceleration commands	More robust control system and algorithms	
Machine vibration / tool resonance	Improve stiffness and damping	
Periodic patterning in work tool surface geometry	Randomization of motions to minimize periodicity	
Tool deformation	Improve tool design and stiffness	
Work-piece deformation	Engineered opto-mechanics, reduce load	
Print through in lightweight optics (facesheet)	Post-grind polishing – can be very slow and limited	
Cyclical Tool-wear (instability)	Frequent tool dressing	

Causes & Mitigation of Periodic Surface Errors

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Due to the hardness and relative resistance to wear, some of the “causes” of MSF errors are amplified when fabricating optics from hard ceramics like SiC

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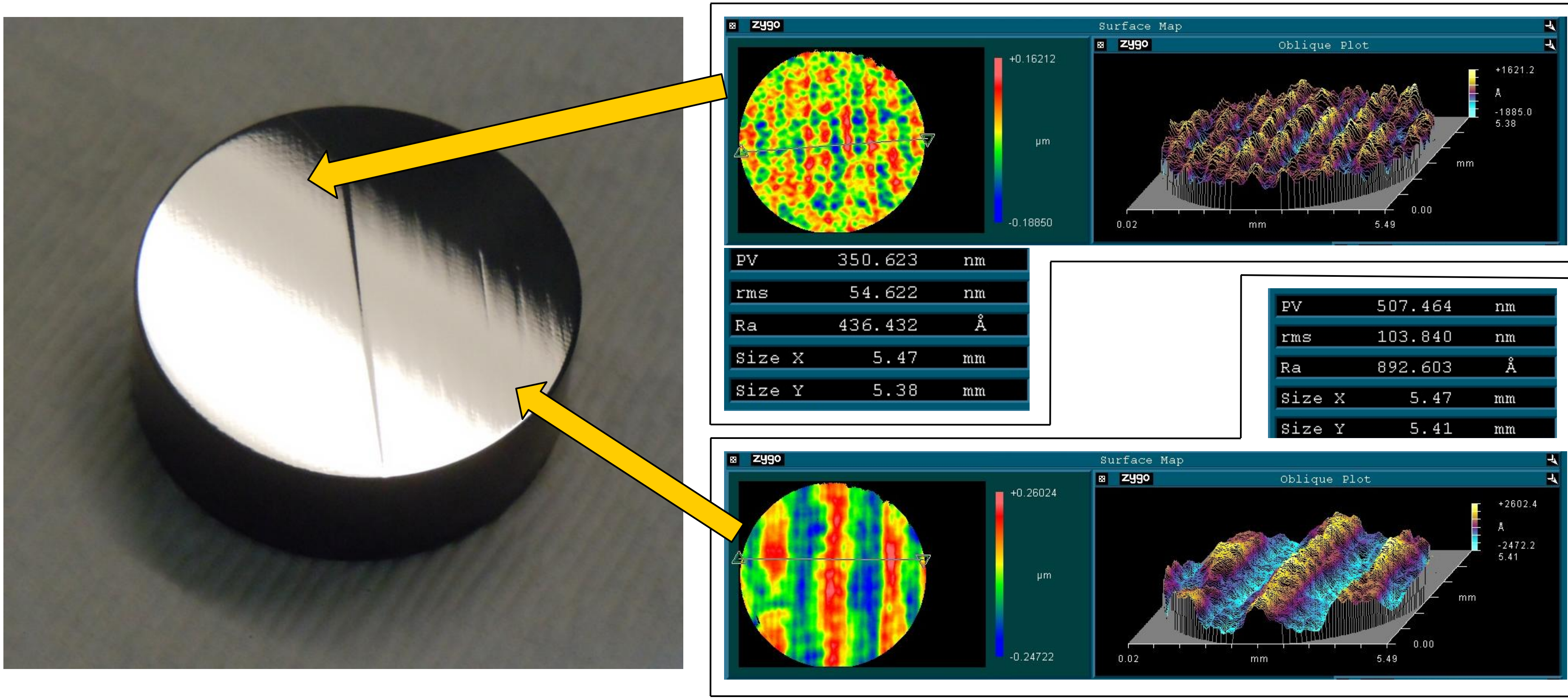
Overlap in raster or spiral sub-aperture tool paths	Post-grind polishing – can be very slow and limited	
Machine (tool) motion control limitations – inability to adequately follow position and acceleration commands	More robust control system and algorithms	
Machine vibration / tool resonance	Improve stiffness and damping	⇦
Periodic patterning in work tool surface geometry	Randomization of motions to minimize periodicity	
Tool deformation	Improve tool design and stiffness	⇦
Work-piece deformation	Support work-piece or feed-forward correction, reduce load	
Print through in lightweight optics (facesheet)	Post-grind polishing – can be very slow and limited	
Cyclical Tool-wear (instability)	Frequent tool dressing	⇦

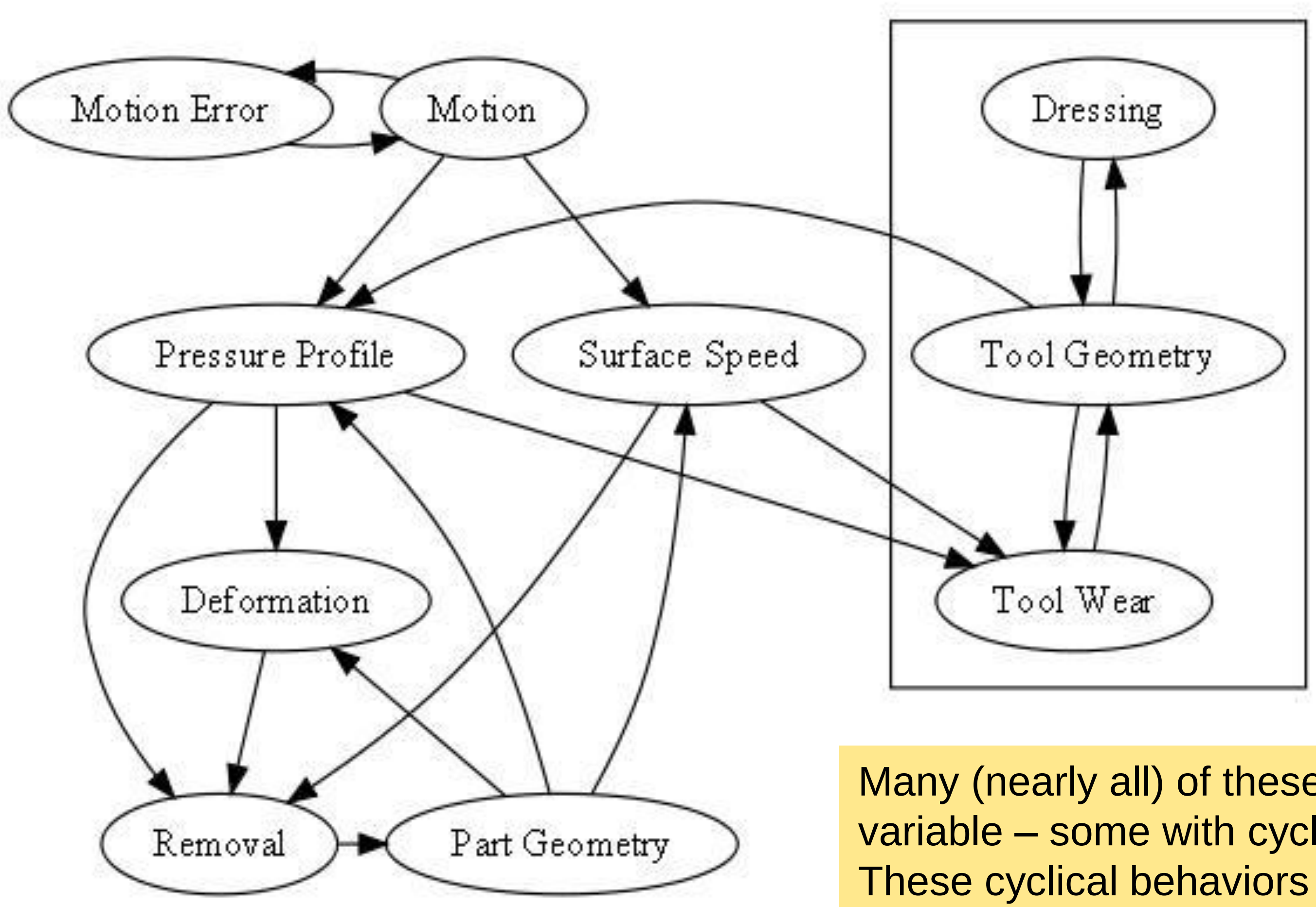
Due to the hardness and relative resistance to wear, some of the “causes” of MSF errors are amplified when fabricating optics from hard ceramics like SiC

As we scale to large optics, we demand longer tool lifetimes between dressing to accommodate longer run times

Recent Results using an OptiPro eSx machine

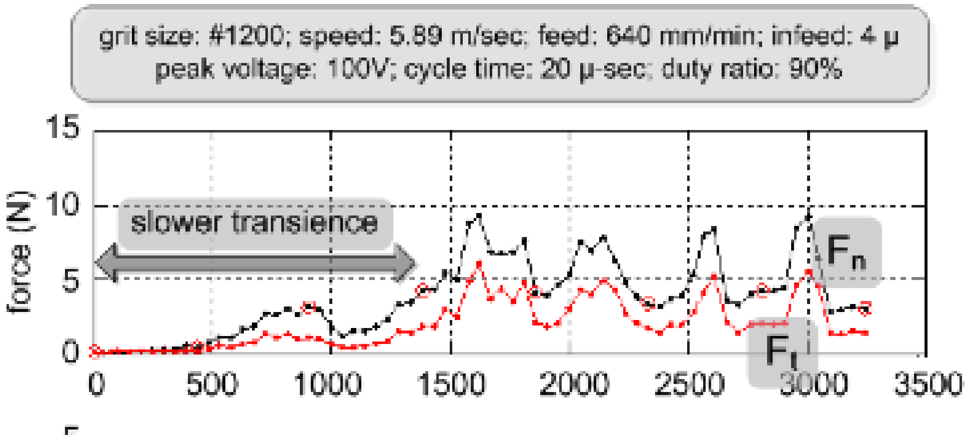


- 1-inch SiC test sample – same tool, different depth of cut and grinding force



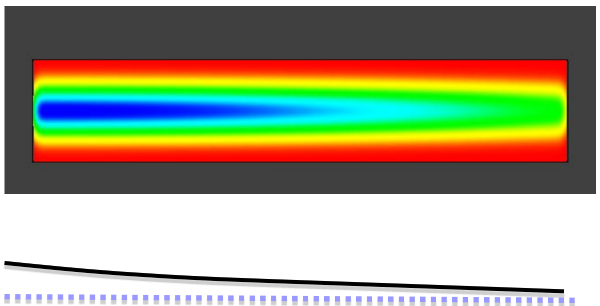
Many (nearly all) of these factors are variable – some with cyclical behaviors. These cyclical behaviors can result in periodic signatures in the surface.

2

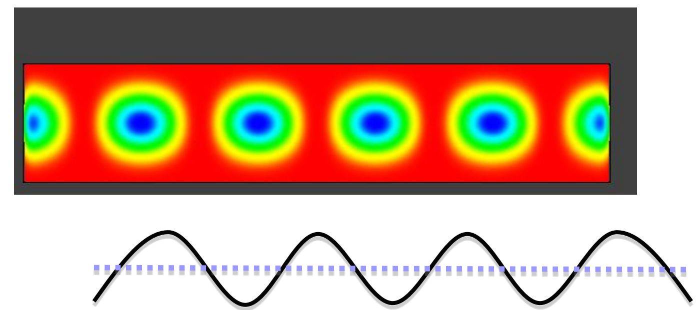


2: BISWAS, PhD Thesis, National University of Singapore, 2009

As the grinding tool cuts the diamonds wear and cutting rate goes down. This increases grinding force (and friction). Eventually abrasive bond breaks downs exposing fresh diamonds and the tool cuts freely again and grinding force goes down. This cycle continues – resulting in a cyclically varying removal rate.



Material Removal Rate Simulation (Glass)



Material Removal Rate (SiC)

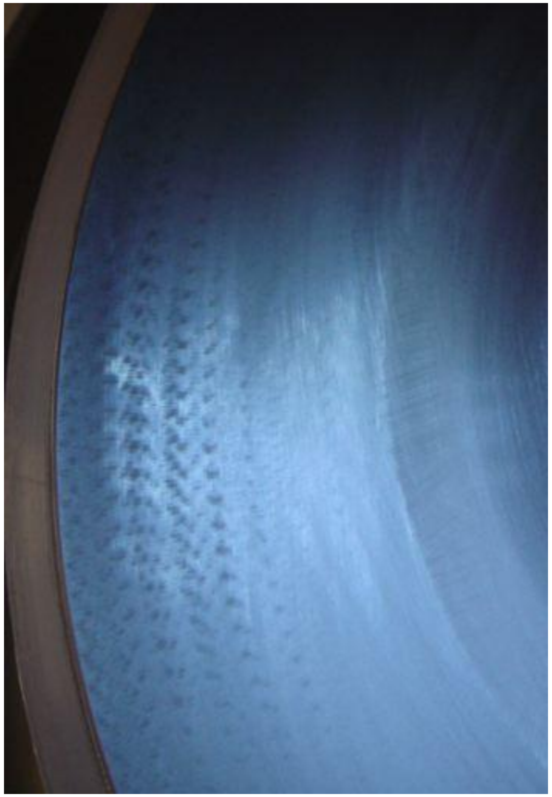
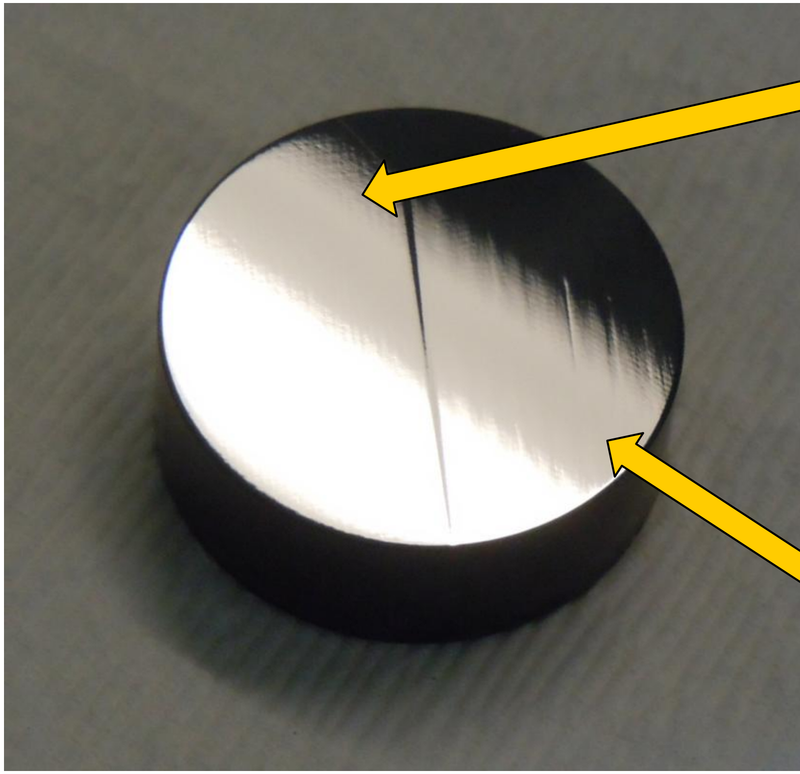
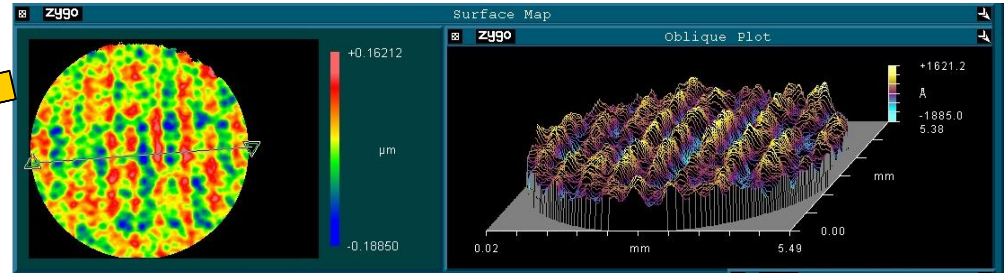


Figure 4: MSF & HSF Artifacts (partially) due to Tool Wear Instability during Grinding

Figure 5: Tool Chatter (Vibration) During Grinding SiC

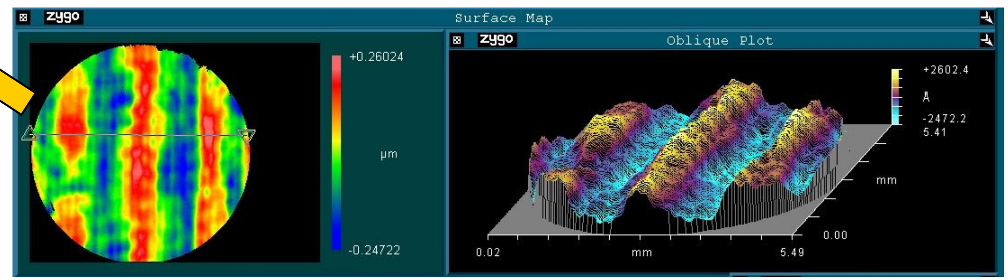
Is it important, how do we measure it, and tolerance it, and how big a problem is it?





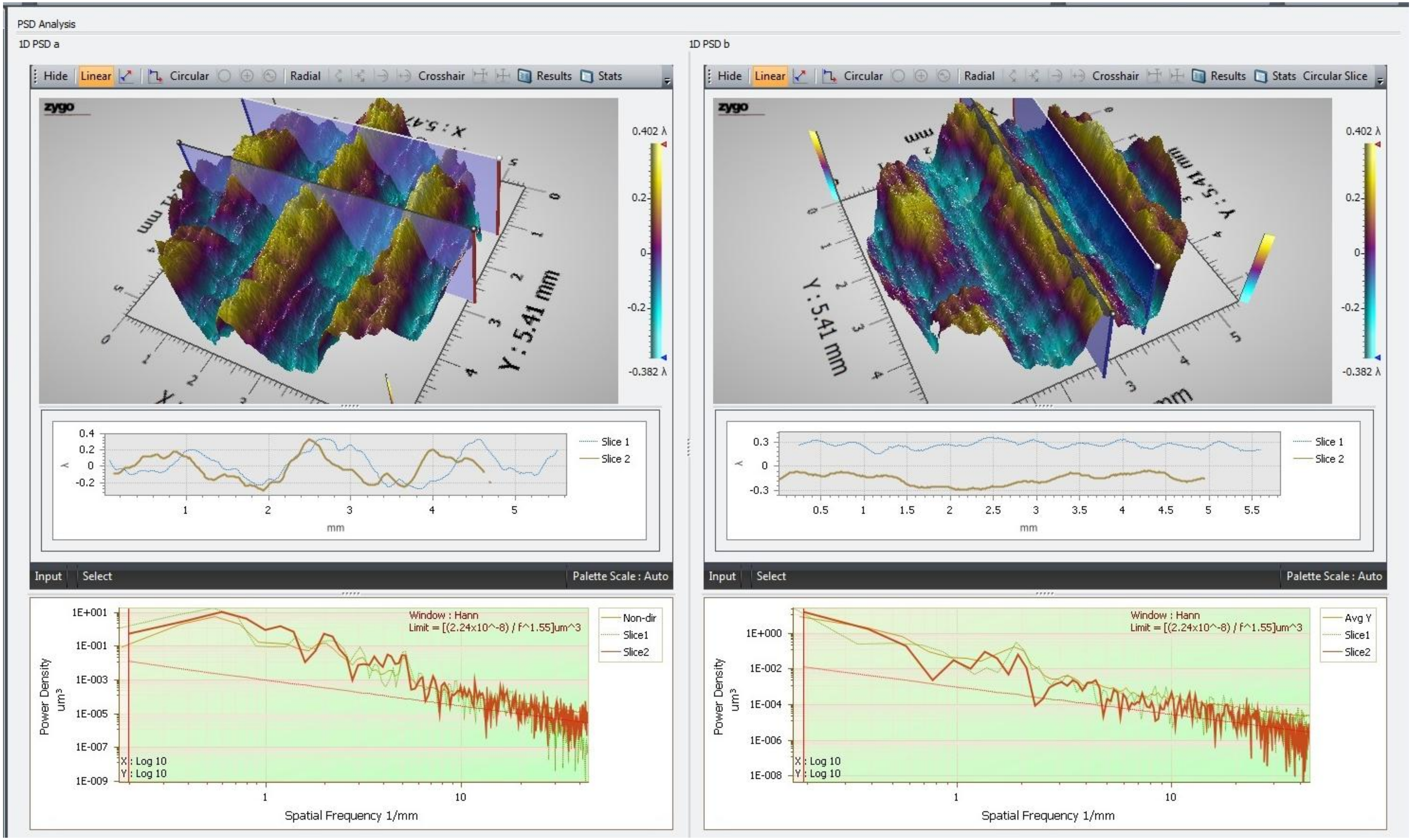
PV	350.623	nm
rms	54.622	nm
Ra	436.432	Å
Size X	5.47	mm
Size Y	5.38	mm

PV	507.464	nm
rms	103.840	nm
Ra	892.603	Å
Size X	5.47	mm
Size Y	5.41	mm



- This previously shown sample was quick polished and measured for roughness, PSD, slope error, structure function and residual errors after subtracting the primary 36 Zernike terms.

PSD using Zygo's new MPx software



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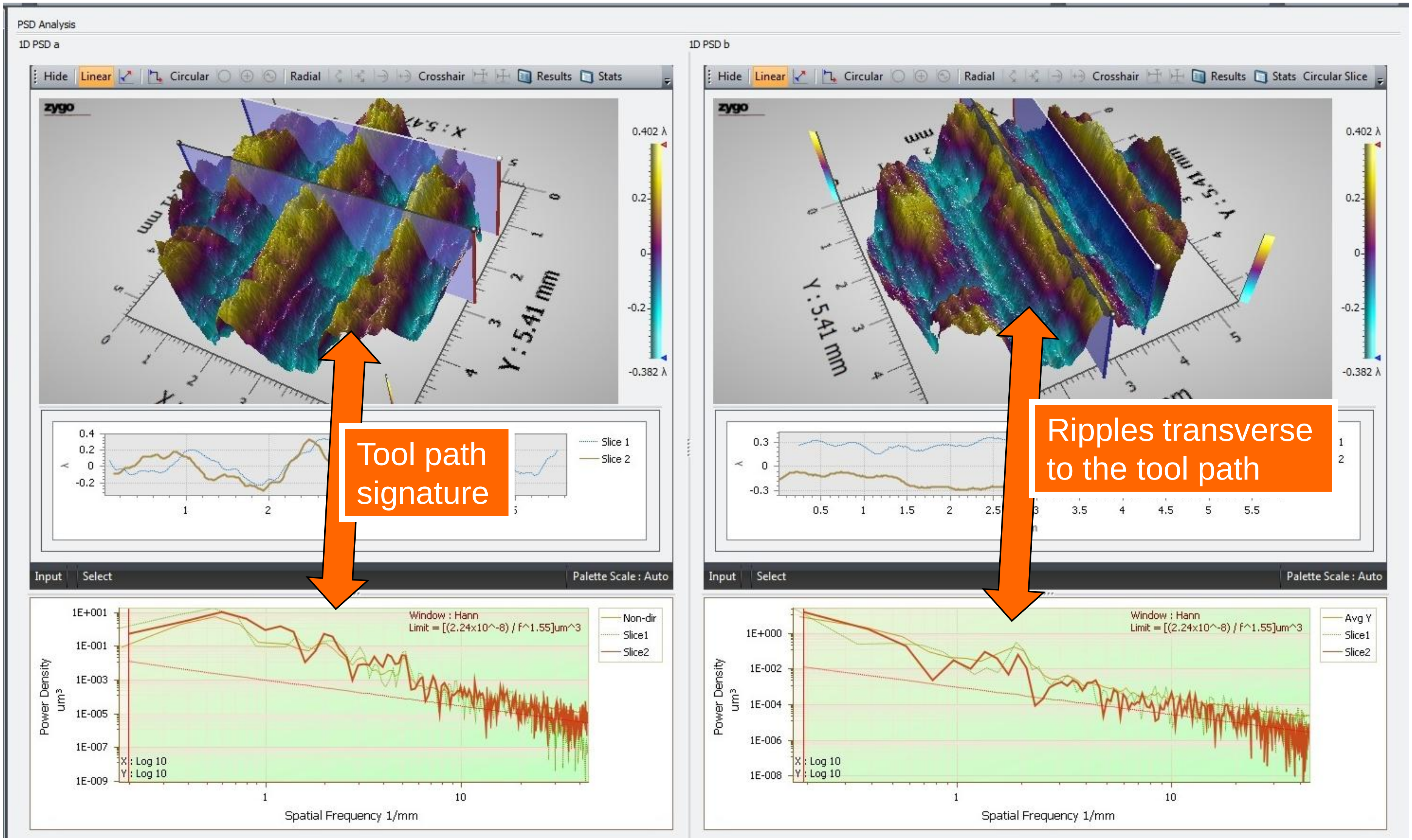
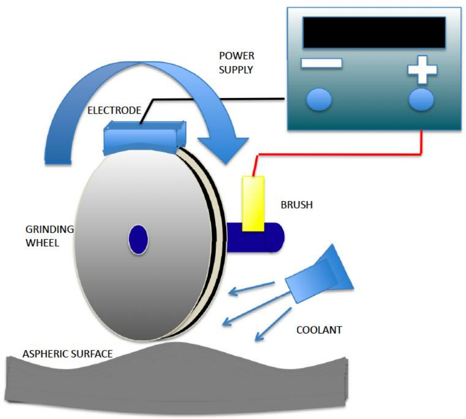


What can we do about it?

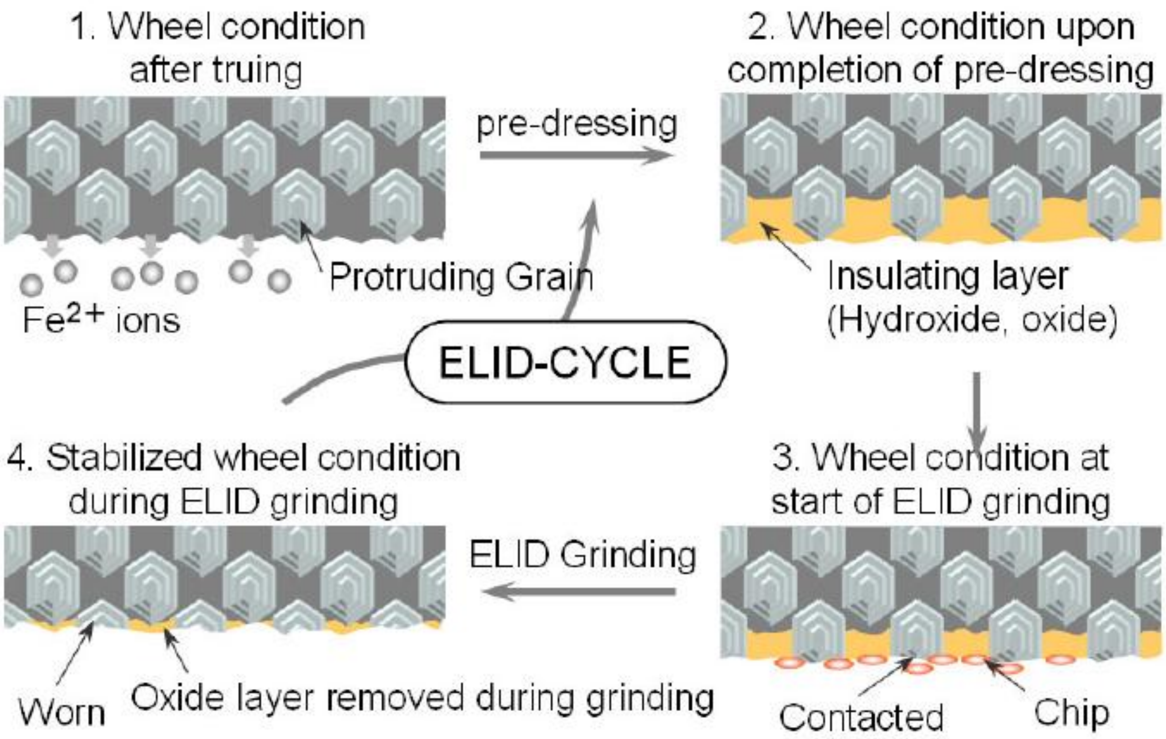
Reduce Grinding load without sacrificing removal rate & introduce continuous dressing – in short reduce the variability in the factors making up the grinding model

- ELID (Electro-Lytic In-process Dressing) may provide a solution to mitigate the creation of MSF errors by
  - Reducing tool load
  - Stabilizing wear rate
  - Reducing vibration in the tool
- ELID may be implemented on small tools for aspheric figuring
- Lends itself to scalability on large machines and large optics.

What is ELID?

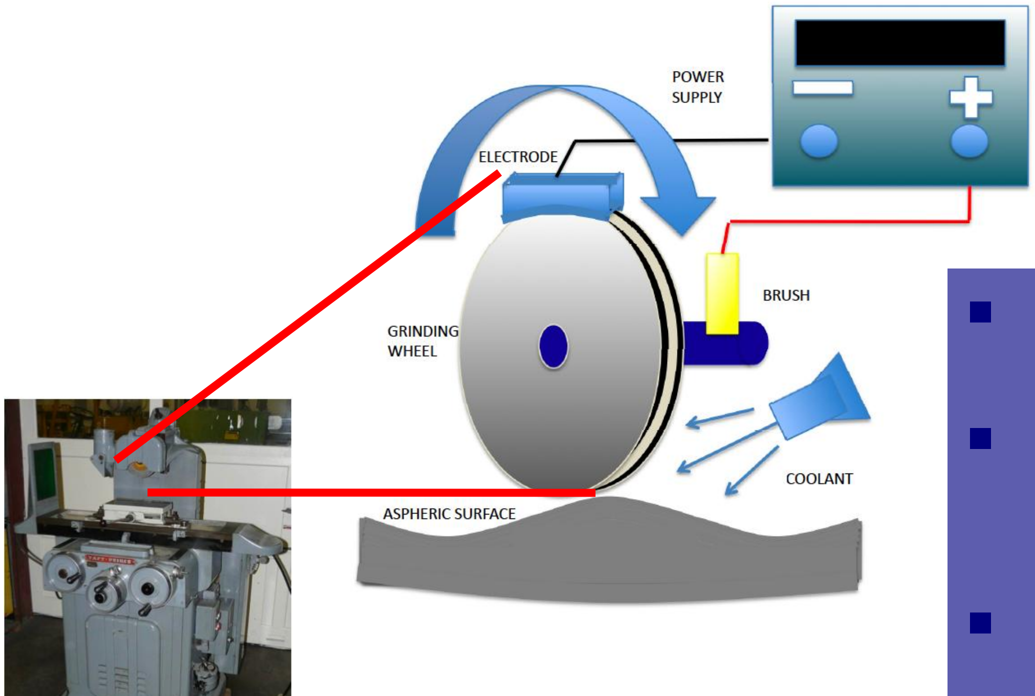


POWER SUPPLY
ELECTRODE
BRUSH
GRINDING WHEEL
COOLANT
ASPHERIC SURFACE



1. Wheel condition after truing
pre-dressing
2. Wheel condition upon completion of pre-dressing
Protruding Grain
Fe^{2+} ions
Insulating layer (Hydroxide, oxide)
ELID-CYCLE
4. Stabilized wheel condition during ELID grinding
3. Wheel condition at start of ELID grinding
ELID Grinding
Worn
Oxide layer removed during grinding
Contacted
Chip

Experimental Design



- Assemble ELID module on a reciprocating surface grinder.
- Determine controls necessary to obtain stabilized tool wear on SiC
- Run glass and SiC samples with and without ELID
- Analyze results by PSD, Structure Function, Slope and Zernike residual errors to detect improvement / isolation of tool wear instability and other factors leading to MSF and HSF errors.

The main demonstrated benefits of ELID are:

- *Rapid, uniform removal of material with fine fixed diamond abrasives on glass and SiC*
- *Reduced surface and subsurface damage*
- *Smooth, low roughness surfaces (typically several nm rms)*

For our purposes, we expect the added benefits of:

- *Reduced vibration-induced MSF features during grinding*
- *Lower tool loading leading to reduced work-piece distortion and print-through*
- *Scalability and insertion compatibility with multiple machine platforms on optics up to 3-meters*

We expect to report results of the conclusions of our study next year